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A NOVEL ARCHITECTURE FOR A RECONFIGURABLE MICRO MACHINING CELL

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Abstract

There is a growing demand for machine tools that are specifically designed for the manufacture of micro-scale components. Such machine tools are integrated into flexible micro-manufacturing systems. Design objectives for such tools include energy efficiency, small footprint and importantly flexibility, with the ability to easily reconfigure the manufacturing system in response to process requirements and product demands. Such systems find application in medical, photonics, automotive and electronic industries.

In this paper, a new architecture for a reconfigurable micro manufacturing system is presented. The proposed architecture comprises a micro manufacturing cell with the key design feature being a hexagonal-base on which three tool heads can be attached to three of its sides. Each such machine-tool head, or processing module, is able to perform a different manufacturing process. These tool heads are interchangeable, enabling the cell to be configured to process a wide range of components with different materials, dimensions, tolerances and specification. Additional components of the cell include manipulation robots and an automated buffer unit. Such cells can be integrated into a manufacturing system via a modular conveyor belt to transfer parts from one cell to another and into assembly. A key consideration of the architecture is a control system that is also modular and reconfigurable; such that when new processing modules are introduced the control system is aware of the change and adjusts accordingly. Further to this coordination, issues between modules and machining cells are also considered. Other design considerations include work-piece holding and manipulation.

This paper provides an overview of the architecture, the key design and implementation challenges as well as a high level operational performance assessment by means of a discrete event simulation model of the micro factory cell.

Keywords: micro manufacturing, reconfigurable manufacturing, flexible manufacturing system.

1.0 Introduction

The idea of producing a flexible Microfactory cell started to arise due to the needs of producing small machined parts using more efficient manufacturing systems and techniques. Therefore, it was necessary to come up with platforms that were suitable for producing micro-size parts. This idea, which developed during the 1990s, had several advantages, such as better use of resources including time, energy and space [1]. Besides this, micro-factories can be represented as fully automated units, which will result in higher precision and productivity levels, and less human involvement during any process. The concept of micro-factory has become essential in a number of industries that require a high level of precision and detail such as semiconductors, microprocessors medical parts (hearing aids) and electronics based industries. Due to the increasing dependence on consumer electronics and IT peripherals, these sectors are expected to continue to dominate micro-technology while other areas like automotives will see a significant decrease.

This concept considers the possibility of offering more than one process or function to be conducted using a micro-factory unit, and since manufacturing systems usually face changes in functions and production methods, it was necessary to develop the current concept of micro-factory to satisfy these changes and configurations by creating reconfigurable micro-factory platforms and modules that could be adjusted in order to perform more than one functionality and production capacity [2]. These recent developments in the micro-factory concept can provide a wider range of products that can be produced by only one platform, which is also a cost effective process because fewer resources will be consumed during each process. In this paper, an overview of the architecture will be presented, followed by a detailed description of the system parts. Then, an operational performance assessment will be addressed in order to validate the design properties.

2.0 Architecture Overview

A new concept of microfactory is presented in this paper, based on satisfying certain objectives, including designing a novel architecture of an easily-reconfigure machining cell that is capable of processing and handling a wide range of micro-component materials within a small footprint and with more energy efficiency. The purpose of designing such a system is to increase the productivity level by performing several machining processes simultaneously, reducing the set-up time of machining tools, and reducing the material handling process as well.

2.1 Proposed Architecture

The proposed architecture consists of three key components: a machining module, a material handling platform and the control system (Figure.1). These individual components will work in collaboration within the system to deliver the final product. With regards to the machining module, this was designed to have a hexagonal-shaped body and three tool-heads attached to each side. The body is based on a similar shape rotating base which has three workpiece holding fixtures fixed to all three of its sides. This module is responsible for holding raw materials and performing the required machining processes on them. The material handling platform consists of a number of units such as: the cylindrical robot-arm, a buffer unit, and a material transfer belt. This platform transfers micro-components to the machining modules as raw materials, and places them using the robot-arm, onto the holding fixtures, enabling the tool-heads to perform the required machining processes on them. Afterward, the same arm will pick up the workpiece, as finished goods, in order to place them on the transfer belt which will move these materials to the buffer unit. All these activities will be managed by a dedicated control system in order to obtain an improved work environment. This architecture has a footprint of 2300 mm (w), 1190 mm (h), which means that all the system's components will fit within this area.

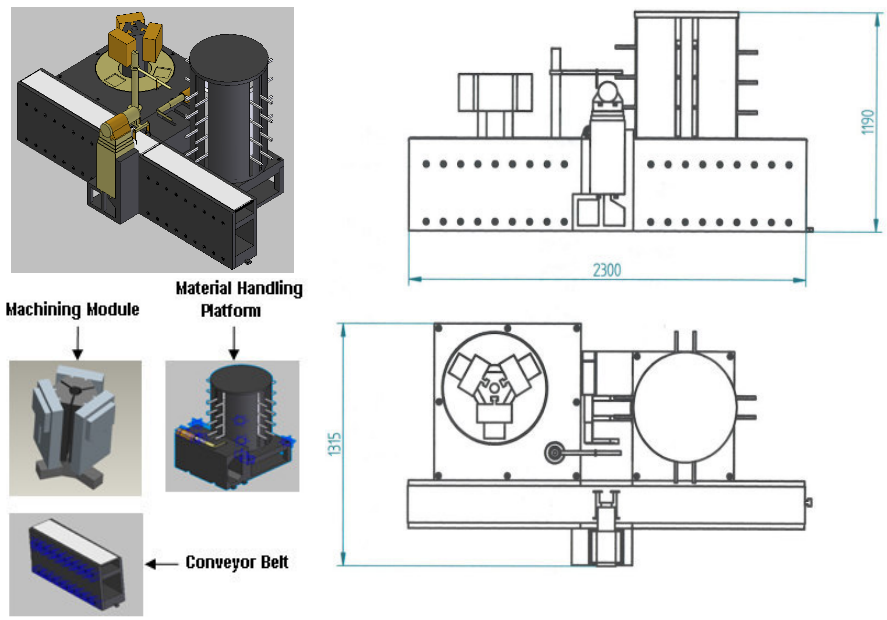


Fig.1. General view of the microfactory cell, showing main components and dimensions in millimetres (mm).

3.0 Key Design and Implementation Challenges

During the design stage of this system, several design and implementation issues have been taken into consideration including: the effect of operating three tool-heads simultaneously, maintaining the lowest level of vibration during each machining stage, and changing tool-heads smoothly. Each one of these issues has been resolved using designing, operating and controlling approaches.

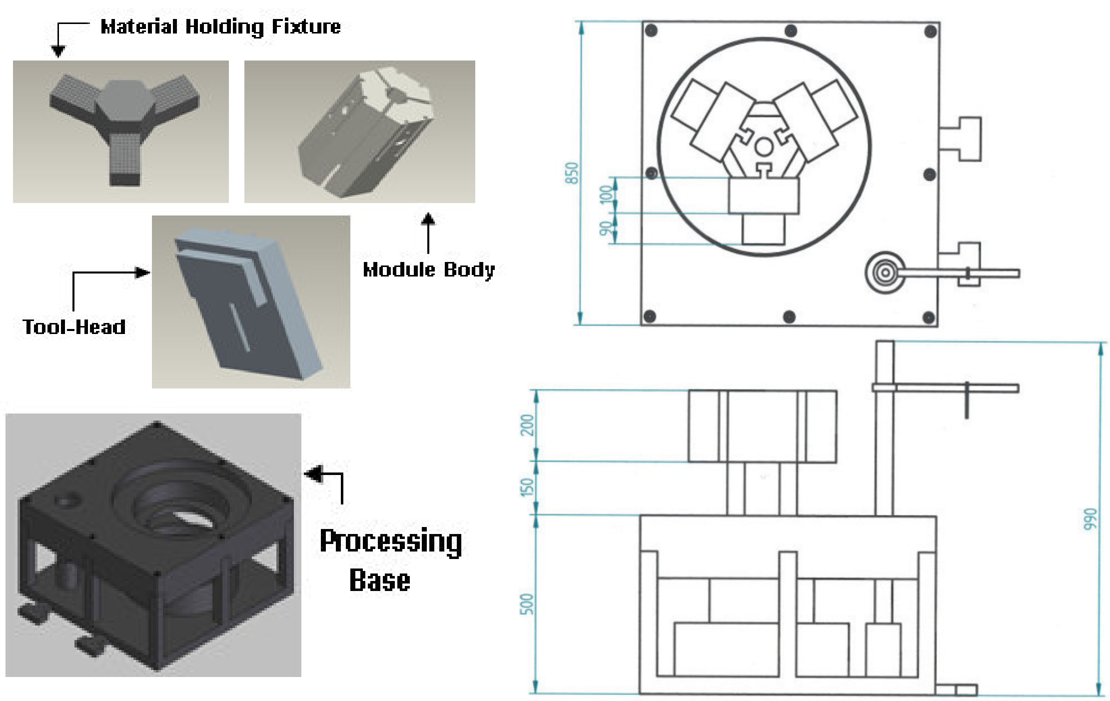


Fig.2. General and detailed views of the proposed machining module, including dimensions, in millimetres (mm).

3.1 Hexagonal Body

Fig.3. Top and general views of the module's hexagonal body.

Starting with the machining module, which represents the core of this system (Figure.2), the main body is designed to have a hexagonal shape (Figure.3). Moreover, the reason for choosing a hexagonal-shape is because it allows the fitting of three tool-heads on its outer sides. Also, it provides increased weight distribution and balance between the module's parts, since the module's body has a symmetric design, which means that all tool-heads will have the same design and properties, and the distance between each tool-head and the other will be precisely the same. Therefore, any physical contact between the tool-heads will be avoided. Moreover, this body contains vibration isolation gaps which separate the three tool heads from each other. The purpose of this feature is to increase the isolation level between tool-heads in order to improve the level of accuracy in the system.

3.2 The Module's Base

The previous hexagonal body is based on a similar hexagonal base with three fixtures attached to its sides. This base represents the moving part of the module which rotates in order to place each fixture under one of the tool-heads (Figure.4). Also, the hexagonal part of the base contains a damping system which is used to reduce the vibration of the module's body during each machining stage. The attached three fixtures have been designed based on a modular concept which increases the system's flexibility and reduces the required set-up time. The design of these fixtures allows jaws and clamps to move automatically to hold the workpiece. This technique is crucial in this cell due to the variety of the workpiece design, size and material.

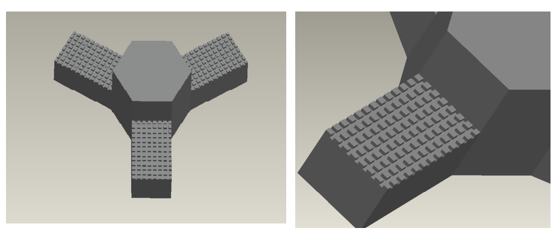


Fig.4. Views of the base unit and material holding fixtures

3.3 Tool-Heads

The three tool-heads in this module share an identical *BASE* structure including design, dimensions and material. However, the machining tools will vary due to the machining nature of each process. According to the module's re-configurability, this design should allow the operator to change each one of these tools with another new tool. The module's body has been designed to provide better physical and electrical contact with each tool, it contains two rectangular cavities that allow the tools base unit to slide and connect to the module's body. The circular connector between the two cavities is an air-suction unit, while the third part is a rectangular power connector. The mechanism of this assembly process is simple; first, the tool will slide into the body's two assembly paths that have a similar structure which matches the body's features. Then, as soon as the power connector in the module is connected to the power socket in the tool, the suction unit will work using a vacuum-mechanism to guarantee that both parts are well-connected and they can perform the designated process. The same procedures can be applied on the other two tools in order to have the final completed module.

3.4 Machining Processes

In order to present a wide range of produced parts, three different processes have been chosen to be performed in this Microfactory system: Micro EDM-Milling, Micro EDM-Drilling, and Laser Machining. The reason for choosing these processes can be justified; Electrical Discharge Machining can be miniaturized and fitted to Microsystems due to their simple mechanical setup and design [3], which can provide high efficiency and space saving opportunities. Moreover, Micro-EDMs have a number of advantages over other machining processes, such as cutting and drilling, because they are a non-contact machining technique using thermal energy like plasma, allowing it the capability to produce high precision products with much less tool breakage problems. The main concept of this technique is machining complex shapes using high speed rotation of a simple shaped electrode [4]. Laser technology has always been capable of providing top-class machining on small scale, due to the wide range of its application, such as engraving and surface finishing [5]. This technology can also be used with several types of material such as metals, ceramics, polymers and silicon.

4.0 Design Analysis of Machining Module

An initial dynamic FEA model has been developed to examine the dynamics of the machining module. Several inputs have been assumed at this stage of design: Motor speed (3000 rpm or 50 Hz), module's material (Granite body, Steel tool-heads, and cast iron base), and Base Damping (2%). At this stage, we assumed that the damping level of the base is equal to natural damping in order to examine the limits of this design. Based on this analysis, six natural frequencies have been observed: 121.6 Hz, 125.2 Hz, 128.3 Hz, 210 Hz, 212 Hz and 234.7 Hz (values higher than 234.7 Hz have been ignored due to their insignificance to the design). Figure 5 shows the reaction of the module during each one of the above natural frequencies.

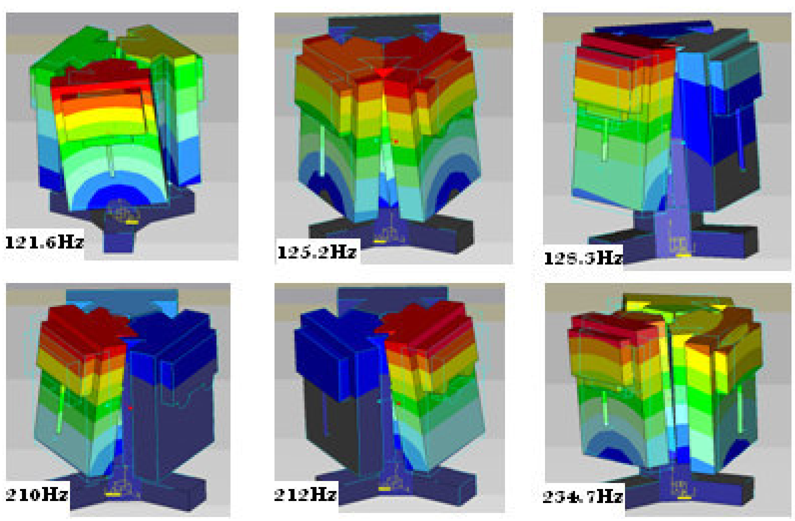


Fig.5. The module's reaction to six natural frequencies.

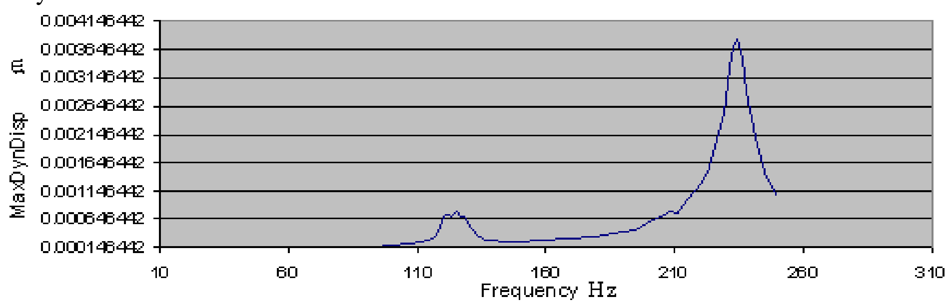
Moreover, based on these natural frequencies, both dynamic displacement and stress have been calculated. Additionally, according to these calculations (figure.6), two peaks have generated on frequencies (125.2 Hz) and (234.7 Hz). However, the module has an acceptable dynamic structure since both levels are low in considering the damping level of the hexagonal base. This is an important step in the design process due to the level of accuracy required during the machining stage.

5.0 Material Handling Platform

The other main part of the system, which is the platform, is in charge of material handling within this system. Furthermore, the control system will be considered as part of this platform due to its position in the system's layout.

5.1 Control Unit

The control unit will be mainly responsible for controlling the overall movement and function of the machine. This includes: activating the different parts on the cell that include the pumps and motors, controlling the mechanical parts in the system including fixtures, Grippers, and movement/operation of the tools. Connecting this unit to a database will be essential in monitoring the system's performance and use of the collected data to improve the system in the future.



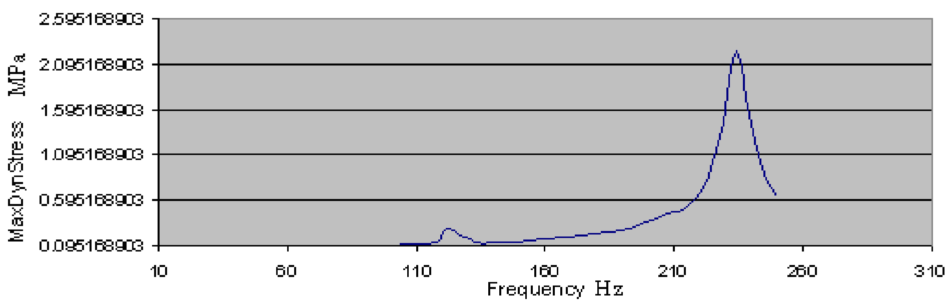


Fig.6. Dynamic displacement and stress Vs. Frequency.

5.2 Material Transfer Module

An automated mechanism is needed to be designed to transport material from one machine to another. From the mechanism's viewpoint, the material will be transported using a standard pallet. Thus, the simplest method would be the use of conveyor belts with appropriate width to accommodate the pallets. The module (Figure.7) would be built in standard sizes that could then be connected to each other in the desired layout.

5.3 Buffer Module

This module is aimed to temporarily store work-in-progress (WIP) by acting as a buffer between cells. The cell layout is supposed to be linked with a number of other similar cells that will provide the complete process line for mass manufacturing. It is expected that some machines will perform slower than others, or that there will be different components that will require different processes. This means that one cell would need to handle more than one pallet at a time in order to free the conveyor belt for other passing pallets. For this reason this module has been designed (Figure.8) to temporarily store WIP and retrieve it when the processing module is available, then transfer finished pallets back onto the conveyor belt.

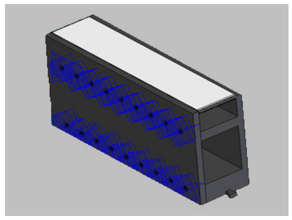


Fig.7. Conveyor Belt Module

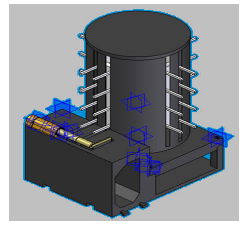


Fig.8. Complete Buffering Module

5.4 Cylindrical Robot-Arm

A cylindrical robot is employed, as shown in Figure.9, to pick and place components from the pallet to the holding fixtures, and vice versa. The robot chosen for this application is a simple 'cylindrical robot' which is usually a custom made item. The one shown in the figure below is merely a structure to show its position and the robot's main components.

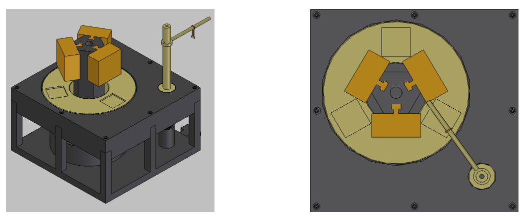


Fig.9. General and Top view of the Robotic-arm position

6.0 Operational Performance Assessment

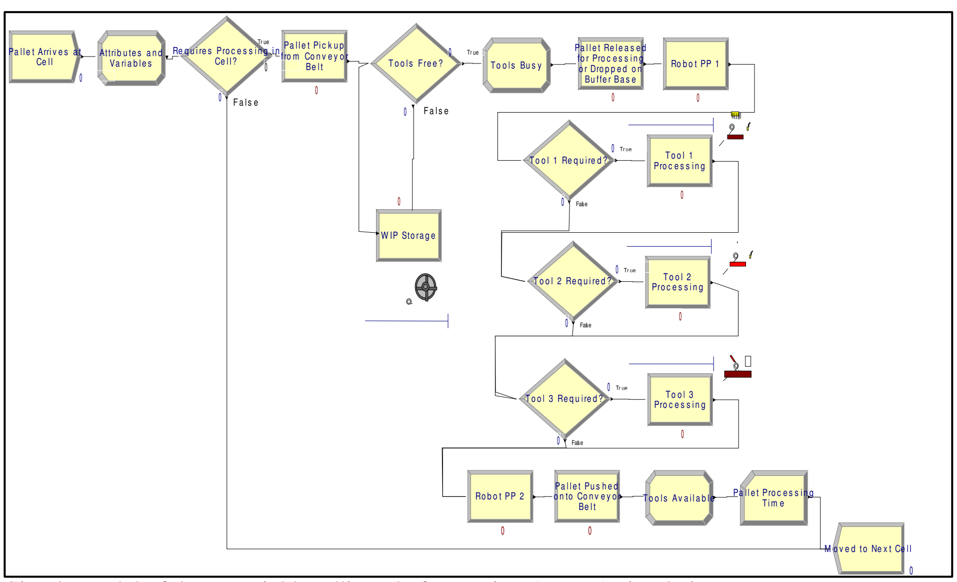


Fig.10. Simple model of the material handling platform using ARENA simulation.

Following the completion of the design it was important to perform an initial test in order to examine operational performance of the cell. A simulation model using *ARENA* [6] has been developed (Figure.10) to offer a simple demonstration of the machine's behaviour, since all timings are estimated values, as the actual machine is just a design that hasn't been manufactured yet (Table. I). However, the simulation provides some idea of what parameters the machine will run on and most importantly an estimated pallet processing time.

The aim of the simulation is mainly to understand the operational performance of the cell. This is measured in terms of queuing and utilization of resources. In figure 11, the work in progress (WIP) buffer is showing the highest utilization. Also, queues were only observed by the simulation model in the buffer and no other queues were observed in the system. This initial result confirms that there is no other build-up of queues anywhere else in the system, and enables simpler operational control of the cell as scheduling needs only to be concerned with controlling the queue in the WIP buffer. The second most utilized are the tools as they are also always in operation, but only handle one pallet at a time. The other processes show much less utilization since they are used much less relative to the WIP storage unit and tools. Results from the simulation also show that on average a pallet takes 6.5 minutes to exit the cell, recording a maximum time of 10.2 minutes and a minimum of 3.9 minutes. Results are in the expected range given the total lengths of time for processing, storage and transportation entered. Moreover, this run also shows that WIP storage is the only unit in the system that stores pallets.

TABLE I. Input Parameters

Resource	Input	Units
Pallet arrives at cell	Constant distribution {0.7}	Min per Pallet
Pallet pickup from belt	Triangular distribution {0.05,0.08,0.08}	Min per Pallet
WIP storage	Constant distribution {0.2}	Min per Pallet
Pallet released for processing	Constant distribution {0.3}	Min per Pallet
Component placed on fixtures by Robot-arm	Triangular distribution {0.3,0.4,0.5}	Min per Pallet
Total process time	Triangular distribution {2.5,3.1,3.7}	Min per Pallet
Tool 1(Micro EDM-Drilling)	Triangular distribution {0.3,0.5,0.7}	Min per component
Tool 2 (Micro EDM-Milling)	Triangular distribution {0.7,0.9,1.1}	Min per component
Tool 3 (Laser Machining)	Triangular distribution {1.5,1.7,1.9}	Min per component
Component picked up from fixtures by Robot-arm	Triangular distribution {0.3,0.4,0.5}	Min per Pallet
Pallet pushed onto belt by pushing unit	Constant distribution {0.5}	Min per Pallet

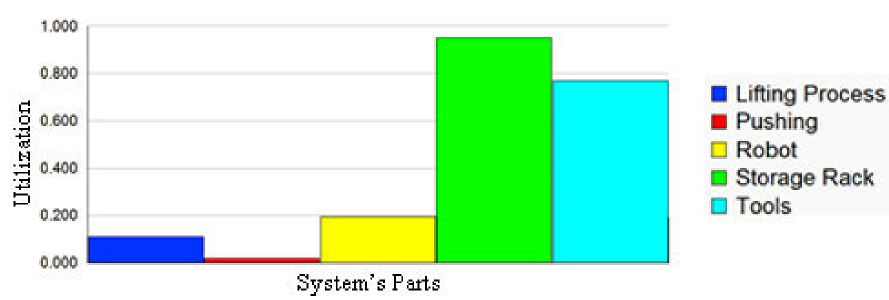


Fig.11. Resource utilization graph

7.0 Conclusion and Future Work

In this paper, we presented the initial design of a reconfigurable micromachining cell and discussed the design considerations of its key components. These include a hexagonal-base with modular fixtures, interchangeable toll-heads for performing a variety of processes, work-piece manipulation and work in progress storage components, and an adaptable control system. Flexibility, re-configurability and a small footprint have been the key design goals considered in this development. This entails that various complements of our cell to be assembled together in a variety of combinations and different layouts into a complete micro-factory, and reconfigure these cells by adding or replacing processes to accommodate production demands as these change.

Our approach in this development is iterative. In this paper, focus was on the presentation of the conceptual architecture design of our micro-manufacturing cell, including the results of our preliminary dynamic FEA analysis of the processing module and the operational performance of the whole cell with simulation. These results confirmed several of our design goals and allowed further progress of this development. The next step in our development is to elaborate this architecture more with detailed design specifications, including detailed FEA modelling of the cell. Then, we aim to build a prototype based on that specification. Further considerations that must still be addressed include the control system, which itself must also be dynamic and flexible entailing a "plug and play" approach, and the design of fixtures.

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